Dynamics of soil hydraulic properties during fallow as affected by tillage

D. Moret*, J.L. Arrúe

Departamento de Edafología, Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (CSIC), PO Box 202, 50080 Zaragoza, Spain

* Corresponding author.

Telf: +34 976 716122

Fax: +34 976 716145

E-mail address: david@eead.csic.es

Abstract

There is limited information on the effects of tillage practices on soil hydraulic properties, especially changes with time. The objective of this study was to evaluate on a long-term field experiment the influence of conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) on the dynamics of soil hydraulic properties over three consecutive 16-18 month fallow periods. Surface measurements of soil dry bulk density (ρ_b), soil hydraulic conductivity ($K(\psi)$) at –14, -4, -1 and 0 cm pressure heads using a tension disc infiltrometer, and derived hydraulic parameters (pore size, number of pores per unit of area and water-transmission porosity) calculated using the Poiseuille's Law were taken on four different dates over the fallow period, namely, before and immediately after primary tillage, after post-tillage rains and at the end of fallow. Under consolidated structured soil conditions, NT plots presented the most compacted topsoil layer when compared with CT and RT. Soil hydraulic conductivity under NT was, for the entire range of pressure head applied, significantly lower ($P<0.05$) than that measured for CT and RT. However, NT showed the largest mean macropore size (0.99, 0.95 and 2.08 mm for CT, RT and NT, respectively; $P<0.05$) but the significantly lowest number of water-conducting pores per unit area (74.1, 118.5 and 1.4 macropores per m^2 for CT, RT and NT, respectively; $P<0.05$). Overall, water flow was mainly regulated by macropores even though they represented a small fraction of total soil porosity. No significant differences in hydraulic properties were found between CT and RT. In the short term, tillage operations significantly increased K ($P < 0.05$) for the entire range of pressure head applied, which was likely a result of an increase in of water-conducting mesopores despite a decrease in estimated mesopore diameter. Soil reconsolidation following post-tillage rains reduced K at a rate that increased with the intensity of the rainfall events.

Keywords: Tillage management; Hydraulic conductivity; Fallow period.

1. Introduction

In Central Aragon (NE Spain), the traditional cereal/fallow rotation is the most common cropping system, which includes a fallow period 16-18 months long. Mouldboard ploughing during the early spring followed by repeated shallow tillage operations, remains the commonest form of fallow management. Tillage alters the structure of the topsoil layers and consequently their hydrophysical properties thus modifying the soil water regime. In order to define sustainable fallow management practices, knowledge of the dynamics of soil bulk hydraulic properties during fallow under field conditions thus appear to be of paramount importance.

With regard to the effects of tillage on the soil hydraulic properties under well-structured soil conditions, results for the different tillage treatments are not always consistent across locations, soils and experiment designs (Green et al., 2003). Chan and Heenan (1993) and McGarry et al. (2000) observed higher values of hydraulic conductivity (K) under no-tillage relative to tilled treatments due to a greater number of macropores (Logsdon et al., 1990), increased fauna activity and the litter of residues formed by accumulated organic matter (Logsdon and Kaspar, 1995). Other researchers found, however, similar (Sauer et al., 1990) or lower (Miller et al., 1998; Evett et al., 1999) values of K under no-tillage treatment. In other studies where reduced tillage was compared with mouldboard ploughing, minimum tillage provided the highest values of K (Logsdon et al., 1993; Moreno et al., 1997), due to a different pore size distribution in the surface layer rather than to changes in total porosity (Moreno et al., 1997). In general, the water flow for structured soils is mainly conducted by macropores even though they constitute only a very small fraction of the total porosity (Sauer et al., 1990; Reynolds et al., 1995; Angulo-Jaramillo et al., 1997; Cameira et al., 2003).

In spite of the large number of field studies conducted to evaluate tillage effects on the hydraulic functioning of structured soils, the information available in the literature about short-term tillage-induced effects on the hydrophysical properties of agricultural soils and their dynamics over the fallow period is very scarce (Green et al., 2003). Results from studies on this subject have shown that the loosening of surface soil by tillage operations increases the total soil porosity (Logsdon et al., 1999; Miller et al, 1998; Green et al., 2003). On the other hand, although a destruction of macropores and macropore continuity is probable after tillage (Malone et al., 2003), an increase in K has commonly been observed in recently tilled soils (Messing and Jarvis, 1993), probably as a consequence of an increase in the number of active mesopores. Tillage operations, however, have a transitory effect on soil physical characteristics because of the impact of rain on the freshly tilled soil, which promotes a steady breakdown of soil structure (Green et al., 2003). Soil structural changes in recently tilled soil caused by precipitation and associated wetting and drying cycles thus lead to a decrease in K (Cameira et al., 2003; Schwartz et al., 2003), which can be attributed to a reduction in the fraction of conductive mesopores (Messing and Jarvis, 1993) in conjunction with a concomitant increase in bulk density (Mellis et al., 1996). However, as a recent review by Green et al. (2003) has made clear, further research is needed to improve current knowledge of the influence of tillage on the soil hydrophysical properties of freshly tilled soils.

The present work is part of a long-term conservation tillage experiment initiated in 1989 to assess soil and crop responses under different tillage systems in a dryland semiarid cereal-growing area of Central Aragon. The study aimed: i) to evaluate the effect of conventional and conservation tillage systems on soil bulk hydrophysical properties after 8-10 years of trials; and ii) to quantify the dynamics of these soil properties over three long-fallow periods.

2. Materials and methods

2.1. Experimental site and procedures

The site is located at the dryland research farm of the Estación Experimental de Aula Dei (CSIC) in the province of Zaragoza (latitude 41º 44'N; longitude 0º 46'W; altitude 270 m). The climate is semiarid with an average annual precipitation of 390 mm and an average annual air temperature of 14.5 ºC. Soil at the research site is a loam (fine-loamy, mixed thermic Xerollic Calciorthid) according to the USDA soil classification (Soil Survey Staff, 1975). Particle size distribution for the plough layer (0-40 cm) averages 25% clay, 47% silt and 28% sand. Selected physical and chemical properties of the soil for this layer were given in López et al. (1996).

The study was conducted on two adjacent large blocks of plots, which were set up on a nearly level area (slope 0-2%) of land in 1991 (Field 1) and 1992 (Field 2) within a long-term conservation tillage experiment initiated in 1989. The two fields were in a winter barley (Hordeum vulgare L.)-fallow rotation, with each field cropped in alternate years. This study was conducted when both fields were in the long-fallow phase of this rotation, which extends from harvest (June-July) to sowing (November-December) the following year. Field measurements were made during three fallow seasons: 1999-2000 and 2001-2002 fallows in Field 2, after 8 and 10 years of the trial, and the 2000-2001 fallow in Field 1, after 10 years of the trial (Fig. 1).

Three different fallow management treatments were examined: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). The CT treatment consisted of mouldboard ploughing of fallow plots to a depth of 30-40 cm in late winter or early spring, followed by secondary tillage with a sweep cultivator to a depth of 10-15 cm in late spring. In the RT treatment, primary tillage was chisel ploughing to a depth of 25-30 cm (non-inverting action), followed, as in CT, by a pass of the sweep cultivator in late spring. The dates of the primary and secondary tillage operations, which were the same for the CT and RT treatments, were 25

April 2000, 10 April 2001 and 13 March 2002 for primary tillage and 29 May 2000, 6 June 2001 and 11 June 2002 for secondary tillage for the 1999-2000, 2000-2001 and 2001-2002 fallow period respectively (Fig. 1a). NT used exclusively herbicides (glyphosate) for weed control throughout the fallow season.

The tillage treatments were arranged in an incomplete block design based on geoestadistical concepts (van Es et al., 1989) with three replications for the RT and NT treatments and four for the CT treatment to ensure a balanced design (López and Arrúe, 1995). In this way, each pair of treatments (i.e., CT-RT, RT-NT and CT-NT) forms an incomplete block in three locations. With this design, the adverse effects of soil spatial variability are reduced by making short-distance treatment comparisons. In addition, by keeping this distance constant, it is ensured that all contrasts are made with equal precision. The size of the basic plot was 33.5 m x 10 m, with a separation of 1 m between plots. Within each incomplete block a 7 m x 7 m region was delimited for either sampling or the in situ measurement of the different soil properties considered in the study. Two observation points existed in each region, one per treatment, separated by a distance of 5 m (López and Arrúe, 1995). With this sampling scheme, a total of 18 measurements (6 per treatment) were made on each fallow field per soil property, sampling depth and observation date. To compare the effects of tillage treatments, analysis of variance (ANOVA) was used for the incomplete block design. Duncan's multiple range test was used to compare treatment means. Statistical comparisons of changes in measured K_{ψ}, bulk density and derived parameters with time were accomplished using a longitudinal data analysis for time series for each individual treatment.

Regardless of the type of fallow management system, the percentage of soil surface covered by cereal crop residues at the experimental site was very low (< 30-40%) during the specific fallow periods considered in the study, as reported by López et al. (2003).

2.2. Experimental measurements

Soil bulk density and hydraulic conductivity were measured in the 1-10 cm depth soil layer at four dates during the second year of the fallow period (Fig.1): (a) before primary tillage implemented in January-February (this set of measurements will be called pre-tillage); (b) after primary tillage but before any post-tillage rainfall events had occurred (this set of measurements made in freshly tilled soil in March-April will be called post-tillage); (c) after primary tillage but following a period of intermittent rainfall events in April-May (post-tillage+rain); and (d) during the last phase of the fallow period after secondary tillage practices, at the end of August (late fallow). The schedule of the main soil property measurements in relation to tillage operations and rainfall events is shown in Fig. 1. Measurements of hydrophysical properties under NT were only taken on pre-tillage and late fallow dates. For the 1999-2000 fallow season, field measurements in freshly tilled soil were not possible due to a rainfall of 25 mm on 26-27 April 2000, immediately after primary tillage (Fig. 1). For each observation region and treatment, all the measurements were concentrated in a small area of ≈ 1 m^2.

Daily rainfall data were continuously registered with a datalogger (model CR10, Campbell Scientific Inc.) from an automatic weather station located at the experimental site.

2.2.1. Bulk density

Soil dry bulk density (ρ_b) was determined by the core method with core dimensions of 50 mm diameter by 50 mm height. Core samples were taken near the measurement locations for the hydraulic properties. This sampling was made on the same day as infiltration measurements to determine the antecedent dry bulk density and volumetric water content.

2.2.2. Soil hydraulic properties

The field soil hydraulic properties were characterised at each observation point using a modified Perroux and White (1988) tension disc infiltrometer with a base radius of 125 mm as described by Moret et al. (2004) for structured soils and Moret and Arrúe (2005) for freshly tilled soils. Infiltration measurements were taken on areas cleared of surface crust, large clods and crop residue and brushed smooth. In order to ensure good hydraulic contact between the disc and the soil a thin layer (0.0015 m thick) of commercial sand (80-160 μm grain size) was also poured onto the soil surface. The base of the disc was covered with a nylon cloth of 20-μm mesh. Infiltration runs were performed at four ψ values (namely, -14, -4, -1, and 0 cm, applied in this order and at the same place). For zero supply tension, flow measurements were carried out containing lateral surface flow. Flow monitoring continued until steady-state flow, which was attained when a constant drop-rate in water level of the infiltrometer reservoir was observed. On average, the minimum time to reach a steady-state condition varied from 10 to 45 minutes for the 0 to -14 cm of water pressure head range. Flow readings were automatically recorded every 30 seconds from the drop in water level of the water supply reservoir of the infiltrometer, by using a three-rod TDR probe vertically placed in the center of the water reservoir and connected to a TDR pulser (Tektronix 1502C metallic Time Domain Reflectometer) according to the procedure described by Moret et al. (2004).

The soil hydraulic conductivity, K, at the different water pressure heads (K_{14}, K_4, K_1, and K_0) and the matric flux potential were calculated from cumulative infiltration using the multiple-head method (Ankeny, 1992). The representative mean pore radius, λ_ψ, (White and Sully, 1987) was calculated according to Ankeny (1992)

$$\lambda_\psi = \frac{\sigma K_\psi}{\rho g \phi} \qquad (1)$$

where σ (g s^{-2}) is the surface tension of water, ρ (g cm^{-3}) is the density of water, g (cm s^{-2}) is the acceleration due to gravity, and ϕ is the matric flux potential, calculated according to ϕ_ψ =

K_ψ / α_ψ, where α_ψ is the slope of the ln*K* vs. ψ curve (Ankeny, 1992). The constant α_ψ value between adjacent ψ settings is one of the main assumptions used in steady flow analysis using tension infiltrometry (Reynolds and Elrick, 1991; Ankeny et al., 1991). The number of λ_ψ pores per unit area of infiltration surface, N_ψ, required to produce the measured K was estimated using Poiseuille's Law for flow in a capillary tube

$$N_\psi = \frac{8\mu K_\psi}{\rho g \pi \lambda_\psi^4} \qquad (2)$$

where μ (g cm^{-1} s^{-1}) is the dynamic viscosity of water (Reynolds et al., 1995).

Soil macropores were defined as those pores that drain at $\psi > -4$ cm (pore radius > 0.375 mm; Clothier and White, 1981) and mesopores as those pores draining at ψ between – 4 and – 14 cm (0.375 > pore radius > 0.107 mm). In order to determine the contribution of each pore class to flow we used the "representative mean pore radius for two consecutive soil water tensions" index, $\lambda_{\Delta\psi}$, defined by Moret and Arrúe (2007) as

$$\lambda_{\Delta\psi} = \frac{\sigma(K_i - K_{i-1})}{\rho g(\phi_i - \phi_{i-1})} \qquad i = 1, 2, \ldots n \qquad (3)$$

where n is the number of measurements performed in a sequence and K_i and K_{i-1} the hydraulic conductivity for two consecutive tensions. Therefore, the number of effective $\lambda_{\Delta\psi}$ pores per unit area, $N_{\Delta\psi}$ (Moret and Arrue, 2007) was calculated as

$$N_{\Delta\psi} = \frac{8\mu(K_i - K_{i-1})}{\rho g \pi \left(\lambda_{\Delta\psi}\right)^4} \qquad i = 1, 2, \ldots n \qquad (4)$$

The effective porosity for two consecutive soil water tensions, $\theta_{\Delta\psi}$, is then given by the expression

$$\theta_{\Delta\psi} = N_{\Delta\psi} \pi (\lambda_{\Delta\psi})^2 \qquad (5)$$

The contribution of both macropores and mesopores to the total saturated water flux, φ, was calculated from K_{14}, K_4, and K_0 (Watson and Luxmoore, 1986; Cameira et al., 2003) according to the expression

$$\varphi_i(\%) = \frac{K_i - K_{i-1}}{K_0} x100 \qquad i = 1, 2, \ldots, n \qquad (6)$$

where K_0 is the saturated hydraulic conductivity.

3. Results and discussion

3.1. Weather conditions

Precipitation records over the 3-year experimental period show a high variability in the rainfall pattern for the different fallow periods, particularly around the tillage application dates (Fig. 1). Total precipitation between primary and secondary tillage was in general high and effective (effective rainfall is here defined as rainfall > 10 mm day^{-1}). The effective rainfall between primary tillage and the post-tillage + rainfall sampling was 49, 33, and 61 mm for the 1999-2000, 2000-2001 and 2001-2002 fallow periods, respectively. It is worth noting the intense rainfall event after primary tillage in the 2001-2002 fallow period (40 mm in 24 hours on 16 March 2002). Rainfall from secondary tillage to the late fallow sampling was low.

3.2. Soil bulk density

Table 1 presents the field bulk density (ρ_b) and corresponding θ values measured in the 1-6 cm soil layer at the time of the infiltration measurements under the different fallow management treatments during the three experimental fallow seasons. Overall, the pre-tillage values of topsoil ρ_b after 8-10 years under continuous NT were greater than under CT and RT treatments. Greater soil compaction under NT has been observed in other long-term experiments (Logsdon et al., 1990; Evett et al., 1999; Hernanz et al., 2002; Schwartz et al., 2003; Lampurlanés and Cantero-Martínez, 2003). This fact is commonly associated with the gradual consolidation of the soil matrix over time owing to rainfall and the absence of annual tillage-induced loosening. On the other hand, the lower ρ_b values found 7-8 months after the harvest of a barley crop under RT compared with CT can be related to the greater persistence of the soil loosening after chisel ploughing compared with mouldboard ploughing (López et al., 1996).

As observed by several authors (Sauer et al., 1990; Logsdon et al., 1999; Miller et al, 1998; Mellis et al., 1996; Green et al., 2003), soil loosening in the plough layer after primary tillage tended to decrease ρ_b in the 1-6 cm layer (Table 1; post-tillage). Soil reconsolidation due to post-tillage rainfall events and associated wetting and drying cycles (Mellis et al., 1996; Green et al., 2003) increased ρ_b in tilled plots (Table 1; post-tillage + rain). At this stage, the higher values of ρ_b observed under CT can be related, as mentioned above, with the more unstable topsoil structure induced by mouldboard ploughing. At the end of fallow, and following secondary tillage and additional rainfall events, the soil tends to recover the pre-tillage values of ρ_b (Table 1).

3. 3. Soil hydraulic properties

3.3.1. Soil hydraulic conductivity

Measurements of soil hydraulic conductivity (K) for the different fallow periods and sampling dates, ψ values, and tillage treatments are summarised in Fig. 2. For structured, consolidated soil conditions (pre-tillage sampling) (Fig. 2), NT soil, after 8-10 years of continuous no-tillage management and for the entire range of applied soil water pressure heads, presented K values significantly lower than those observed in CT and RT soils. However, no differences in K were found between CT and RT treatments. These results are similar to those found in other studies (Sauer et al., 1990; Moreno et al., 1997; Miller et al., 1998; Evett et al., 1999).

Over the two available experimental years (2000-2001 and 2001-2002), primary tillage operations in CT and RT plots (post-tillage sampling) significantly ($P < 0.05$) increased K_{14}, K_4 and K_1 (Fig. 2) compared with pre-tillage values. This result is in agreement with findings in other studies (Sauer et al., 1990; Messing and Jarvis, 1993; Cameira et al., 2003), in which greater infiltration rates were measured after tillage due to an increase in soil porosity. Unreliable post-tillage infiltration measurements at $\psi = 0$ cm, probably due to the soil macrostructure collapsing below the infiltrometer (Moret and Arrúe, 2005), were discarded from the analysis. No differences in K were observed between CT and RT treatments.

Rainfalls following primary tillage (post-tillage + rain sampling) affected K under CT and RT because of soil structural changes caused by subsequent wetting and drying cycles (Angulo-Jaramillo et al., 1997). In general, a decrease in K_{14} was observed (Fig. 2). The changes in K were statistically significant ($P < 0.05$) in the 2001-2002 fallow period, probably due to the high effective rainfall (61 mm) received after primary tillage (Fig.1), which resulted in a greater decrease in K_{14} and K_4 as compared with the 2000-2001 fallow, with only 33 mm of effective precipitation (Fig. 1). Overall, the high values of K in late fallow (Fig. 2), 2-3 months after secondary tillage (Fig. 1), can be explained by the scarce rainfall events recorded in that period, which did not allow a complete soil reconsolidation. The K_o values for CT and RT in the 2000-2001 fallow are not shown in Fig. 2 due to inconsistent soil water flow values, as explained above.

3.3.2. K, λ_ψ and N_ψ relationships

Regardless of the tillage treatment, the λ_ψ and N_ψ vs. K relationships at 1 cm depth for structured soil conditions (pre-tillage sampling) (Fig. 3) were similar to those reported by

Reynolds et al. (1995). The effective equivalent mean pore radius, λ_ψ, was relatively constant at its minimum value of about 0.1 mm for low K, but then increased with increasing K at higher levels of K. On the other hand, the number of effective water-transmitting pores per unit area, N_ψ, which is inversely related to λ_ψ,to the fourth power, increases when K decreases (Fig. 3). Both λ_ψ and N_ψ were also affected by the different tillage treatments (Fig. 3). For K_{14}, λ_ψ was smaller and N_ψ was greater under NT than under CT and RT ($P < 0.05$). These results are consistent with the higher soil bulk density found under NT (Table 1) (Reynolds et al., 1995).

Primary tillage strongly modified the configuration of the water-transmitting pores within the soil matrix in the CT and RT plots. In general an increase in N_ψ and a reduction in λ_ψ were estimated immediately after tillage (Fig. 3, post-tilage). This behaviour may be the result of soil pulverisation at the soil surface due to ploughing (Sauer et al., 1990), which destroys transmission macropores, thus increasing the number of smaller pores (Malone et al., 2003). There were no significant differences in λ_ψ and N_ψ between CT and RT treatments (Fig. 3).

Post-tillage rainfalls during the 2000-2001 and 2001-2002 fallow periods increased λ_ψ and reduced N_ψ at K_1, but only slightly modified these parameters at K_{14} and K_4 (Fig. 3). These changes, which depend on the amount and intensity of the rainfall events recorded after primary tillage, were more dramatic in the 2001-2002 fallow period (Fig. 3), which was characterised by a high effective precipitation (Fig. 1). In late fallow, the λ_ψ and N_ψ vs K_ψ relationships under CT and RT (Fig. 3d) were similar to those obtained after primary tillage (post-tillage) (Fig. 3). This was due to both the effect of secondary tillage, which loosened the upper 15 cm of soil, and the low rainfall received from the date of secondary tillage until the late fallow sampling (Fig. 1).

3.3.3. Contribution of macropores and mesopores to water flow

The representative mean pore radius for macro- and mesopores, $\lambda_{\Delta\psi}$, and the concentration of $\lambda_{\Delta\psi}$ pores, $N_{\Delta\psi}$, are presented in Figs. 4 and 5, respectively. On average, and regardless of the tillage system, macropores in the pre-tillage sampling had lower $N_{\Delta\psi}$ (18 pores m^{-2}) than mesopores (1400 pores m^{-2}). This resulted in a lower effective porosity $\theta_{\Delta\psi}$ of macropores (Eq. 5) than that calculated for mesopores (Table 2). However, the higher $\theta_{\Delta\psi}$ observed for mesopores did not imply a higher contribution of these pores to the water flux, φ (Table 2). Results indicated that macropores have a larger influence upon water flow than mesopores even though they occupy a much smaller fraction of total soil porosity, as observed by Messing and Jarvis (1993) and Cameira et al. (2003). The pre-tillage values of $\lambda_{\Delta\psi}$ (Fig. 4) and $N_{\Delta\psi}$ (Fig. 5) and $\theta_{\Delta\psi}$ (Table 2) were affected by the tillage treatments. NT macropores thus had a lower $N_{\Delta\psi}$ (1.43 pores m^{-2}) and a lower $\theta_{\Delta\psi}$ (0.0003%) but a greater $\lambda_{\Delta\psi}$ (2.08 mm) than CT and RT macropores (on average, $N_{\Delta\psi}$ = 21 pores m^{-2}, $\theta_{\Delta\psi}$ = 0.0039%, and $\lambda_{\Delta\psi}$ = 0.97 mm). By contrast, whereas no differences in $\lambda_{\Delta\psi}$ for mesopores were detected between tillage treatments, CT and RT in general showed a greater $N_{\Delta\psi}$ and $\theta_{\Delta\psi}$ than NT. In agreement with Miller et al. (1998), it can be concluded that the lower K values under NT are related to a lower number of large pores, even though NT has larger values of $\lambda_{\Delta\psi}$, which is consistent with the significantly greater values of ρ_b under NT (Table 1).

Data available for mesopores after primary tillage showed a significant ($P < 0.05$) reduction in $\lambda_{\Delta\psi}$ (Fig. 4) and increase in $N_{\Delta\psi}$ (Figs. 5) and $\theta_{\Delta\psi}$ (Table 2). Later, wetting and drying cycles associated with intermittent rainfall events after primary tillage contributed to returning the soil mesopore configuration to the initial pre-tillage conditions, as indicated by an increase in $\lambda_{\Delta\psi}$ and a decrease in $N_{\Delta\psi}$ and $\theta_{\Delta\psi}$ (Figs. 4 and 5 and Table 2). These results agree with Messing and Jarvis (1993), who observed a decrease in the fraction of mesopores (for ψ between –6 and –11 cm) after post-tillage rainfalls. However, compared with the pre-tillage conditions, an increase of $N_{\Delta\psi}$ for macrospores was observed under CT and RT in the post-tillage + rain sampling ($P < 0.05$).

Mesopore characteristics in late fallow under CT and RT in the 2000-2001 fallow periods were rather similar to those obtained after primary tillage cultivation (Figs. 4 and 5 and Table 2). In that season, the soil loosening caused by secondary tillage, along with the scarce precipitation that followed this cultivation (Fig. 1), increased $N_{\Delta\psi}$ (Fig. 5) and decreased $\lambda_{\Delta\psi}$ (Fig. 4) for mesopores.

4. Conclusions

Results showed that tillage in the cereal-fallow rotation significantly affected the soil hydrophysical properties in both the long- and the short-term. Thus, after 8-10 years of trial in a long-term tillage experiment in Central Aragon, the structured consolidated soil under no-tillage (NT) presented a more compacted topsoil compared to conventional (CT) and reduced tillage (RT) systems. Regardless of the tillage system, the soil water flow at the soil surface was mainly regulated by macropores, even though this pore size occupies a very small fraction of total soil porosity. However, although a bigger macropore size was observed under NT, the soil hydraulic conductivity near saturation under this treatment was significantly lower than under CT and RT due to a lower number of water-transmitting macro- and mesopores per m^2. Overall, no significant differences in hydraulic properties were found between CT and RT.

In the short-term, the soil hydrophysical properties under CT and RT changed over the fallow period as a function of soil structure modification by tillage operations and subsequent rainfall events. Surface soil loosening caused by tillage decreased the soil bulk density.

Tillage significantly increased the near saturation hydraulic conductivity probably as a result of an increase in the number of water-conducting mesopores. However, an increase in soil bulk density occurred because of soil reconsolidation by post-tillage rains and associated wetting and drying cycles. This entailed a decline in soil hydraulic conductivity. The magnitude of these soil structural changes, which tended to restore pre-tillage conditions, increased with the intensity of the post-tillage rainfall events.

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Figure captions

Figure 1. a) Timing of rainfall and tillage practices (**T**, primary tillage; **t**, secondary tillage) in relation to soil property measurement dates under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) during the experimental fallow seasons (M, infiltration and bulk density measurements at the soil surface under CT, RT and NT; M^*, measurements taken only under CT and RT).

Figure 2. Soil hydraulic conductivity (K) versus pressure head (ψ) relationships measured at 1 cm depth under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) on four dates over the 1999-2000 (Field 2), 2000-2001 (Field 1) and 2001-2002 (Field 2) fallow periods. Bars represent LSD ($P<0.05$) for comparison among tillage treatments where significant differences were found.

Figure 3. Number of effective water-transmitting macropores per unit area (N_ψ) and representative mean pore radius (λ_ψ) versus soil hydraulic conductivity (K) measured at 1 cm depth under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) on four dates over the 2000-2001 (Field 1) and 2001-2002 (Field 2) fallow periods.

Figure 4. Representative pore size for two consecutive soil water tensions, $\lambda_{\Delta\psi}$ (mm) for soil macropores (pore radius > 0.375 mm) and mesopores (pore radius between 0.375 and 0.107 mm) measured at 1 cm depth on four dates during the experimental fallow seasons under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). Bars represent LSD ($P < 0.05$) for comparison among tillage treatments where significant differences were found.

Figure 5. Number of $\lambda_{\Delta\psi}$ pores per unit of area (pores per m^2), $N_{\Delta\psi}$, for soil macropores (pore radius > 0.375 mm) and mesopores (pore radius between 0.375 and 0.107 mm) measured at 1 cm depth on four dates during the experimental fallow seasons under conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). Bars represent LSD ($P < 0.05$) for comparison among tillage treatments where significant differences were found.

Table 1. Average dry bulk density (ρ_b) and volumetric water content (θ) of the surface soil (1-6 cm) determined on four dates over the three experimental fallow seasons before soil hydrological characterisation conventional tillage (CT), reduced tillage (RT) and no-tillage (NT).

		Pre-tillage		Post-tillage		Post-tillage + rain		Late fallow	
Fallow season	Tillage treatment	ρ_b (g cm^{-3})	θ (m^3 m^{-3})	ρ_b (g cm^{-3})	θ (m^3 m^{-3})	ρ_b (g cm^{-3})	θ (m^3 m^{-3})	ρ_b (g cm^{-3})	θ (m^3 m^{-3})
1999-2000	CT	1.22	0.06	-	-	1.17	0.12	1.22	0.03
	RT	1.14	0.07	-	-	1.10	0.14	1.21	0.04
	NT	1.30	0.09	-	-	-	-	1.29	0.05
	LSD†	0.08	NS	-	-	NS	NS	NS	NS
2000-2001	CT	1.28	0.17	1.18	0.09	1.23	0.09	1.29	0.04
	RT	1.23	0.15	1.20	0.09	1.21	0.09	1.28	0.05
	NT	1.37	0.19	-	-	-	-	1.35	0.08
	LSD	0.07	NS	NS	NS	NS	NS	NS	NS
2001-2002	CT	1.25	0.16	1.17	0.12	1.20	0.13	1.17	0.07
	RT	1.17	0.18	1.09	0.10	1.11	0.14	1.07	0.10
	NT	1.38	0.20	-	-	-	-	1.45	0.16
	LSD	0.19	NS	NS	NS	NS	NS	0.14	0.04

† Least significant difference, P<0.05. NS, not significant.

Table 2. Effective porosity ($\theta_{\Delta\psi}$) and contribution to flow (φ) of soil macropores ($0<\psi<4$ cm)[†] and mesopores ($4<\psi<14$ cm)[‡] measured at 1 cm depth on four dates during the experimental fallow seasons under different management treatments (CT, conventional tillage; RT, reduced tillage; NT, no-tillage).

Fallow season	Tillage treatment	Pre-tillage				Post-tillage				Post-tillage+rain				Late fallow			
		Macropores		Mesopores		Macropores		Mesopores		Macropores		Mesopores		Macropores		Mesopores	
		$\theta_{\Delta\psi}$	φ	$\theta_{\Delta\psi}$	φ	$\theta_{\Delta\psi}$	φ	$\theta_{\Delta\psi}$	φ	$\theta_{\Delta\psi}$	φ	$\theta_{\Delta\psi}$	φ	$\theta_{\Delta\psi}$	φ	$\theta_{\Delta\psi}$	φ
		%															
1999-2000	CT	0.0066	69	0.0228	21	-	-	-	-	0.0121	80	0.0113	15	0.0395	71	0.0401	23
	RT	0.0079	77	0.0128	15	-	-	-	-	0.0052	86	0.0056	9	0.0501	76	0.0205	18
	NT	0.0006	79	0.0012	13	-	-	-	-	-	-	-	-	0.0001	77	0.0095	14
	LSD[§]	0.0046	11	0.0085	7	-	-	-	-	NS	NS	NS	NS	0.0101	NS	0.0265	7
2000-2001	CT	0.0027	78	0.0139	16	-	-	0.0731	-	0.0485	57	0.0477	32	-	39	0.0126	-
	RT	0.0013	83	0.0071	14	-	-	0.0042	-	0.0186	72	0.0314	22	-	54	0.0104	-
	NT	0.0003	83	0.0039	16	-	-	-	-	-	-	-	-	0.0018	78	0.0056	14
	LSD	NS	NS	0.0072	NS	-	-	NS	-	NS	NS	NS	NS	-	37	0.0030	-
2001-2002	CT	0.0029	91	0.0041	7	-	-	0.0488	-	0.0062	89	0.0062	8	0.0583	69	0.0321	24
	RT	0.0022	94	0.0027	4	-	-	0.0351	-	0.0079	89	0.0072	9	0.0766	75	0.0215	20
	NT	0.0001	88	0.0016	8	-	-	-	-	-	-	-	-	0.0001	76	0.0052	12
	LSD	0.0022	NS	0.0016	NS	-	-	NS	-	NS	NS	NS	NS	0.0662	5	0.0093	4

[†] Pressure head range defining macropores (pore radius > 0.375 mm) according to the capillary rise theory.
[‡] Pressure head range defining large mesopores (pore radius between 0.375 and 0.107 mm) according to the capillary rise theory.
[§] Least significant difference (P<0.05). NS, not significant

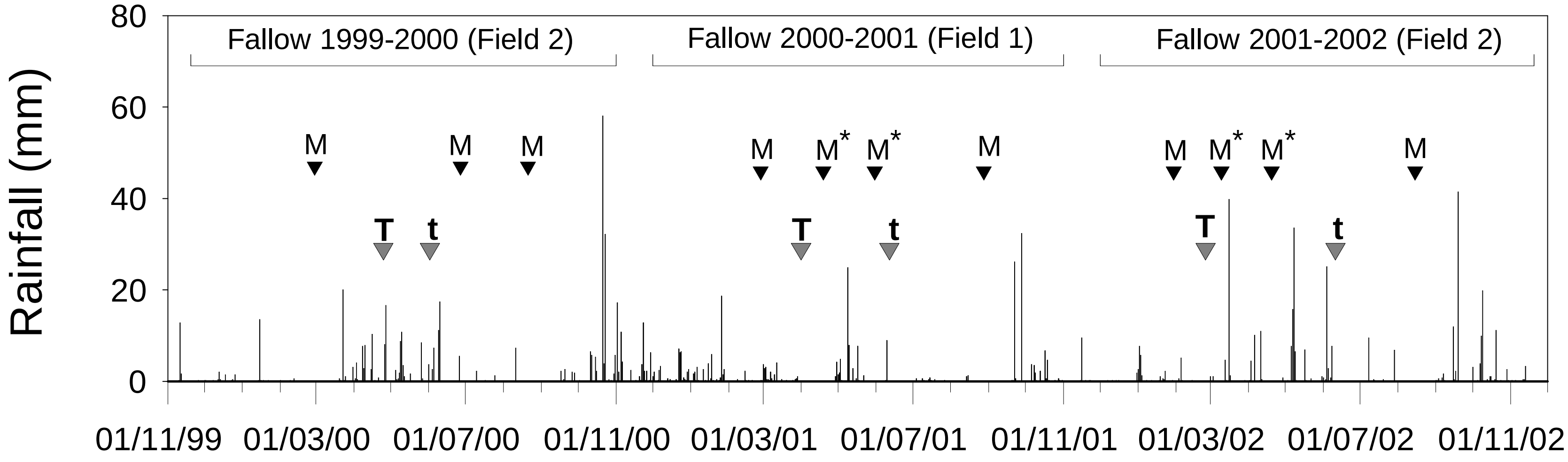
Rainfall (mm)
80
60
40
20
0
Fallow 1999-2000 (Field 2)
Fallow 2000-2001 (Field 1)
Fallow 2001-2002 (Field 2)
M
M
M
M
M*
M*
M
M
M*
M*
M
T
t
T
t
T
t
01/11/99
01/03/00
01/07/00
01/11/00
01/03/01
01/07/01
01/11/01
01/03/02
01/07/02
01/11/02

Fig. 1

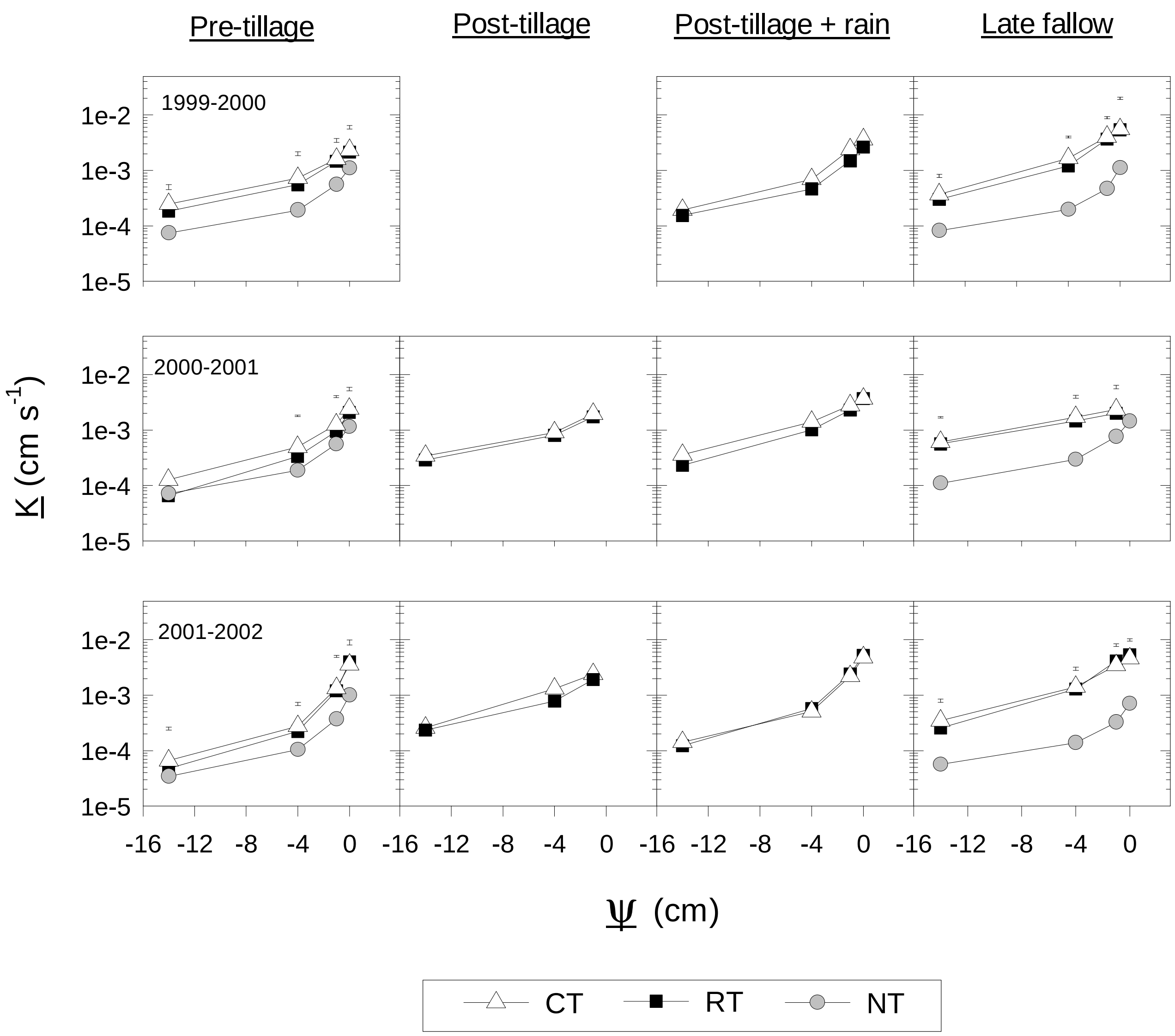
Pre-tillage
Post-tillage
Post-tillage + rain
Late fallow
1999-2000
2000-2001
2001-2002
K (cm s-1)
1e-2
1e-3
1e-4
1e-5
-16 -12 -8 -4 0
Ψ (cm)
CT
RT
NT

Fig. 2

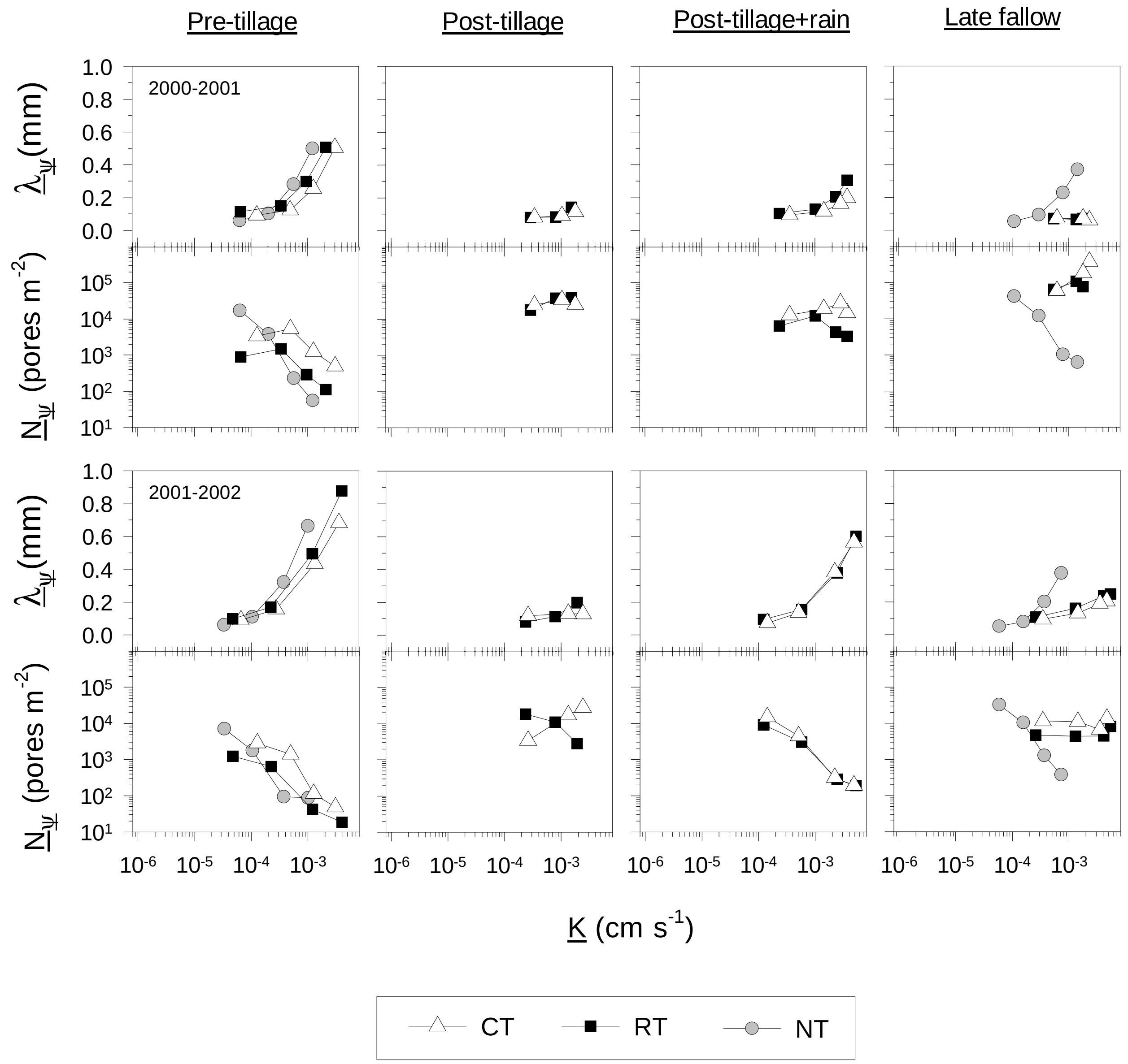
Pre-tillage
Post-tillage
Post-tillage+rain
Late fallow
2000-2001
2001-2002
$\underline{\lambda}_{\underline{\psi}}$(mm)
$\underline{N}_{\underline{\psi}}$ (pores m^{-2})
1.0
0.8
0.6
0.4
0.2
0.0
10^5
10^4
10^3
10^2
10^1
10^{-6} 10^{-5} 10^{-4} 10^{-3}
$\underline{K}$ (cm s^{-1})
CT
RT
NT

Fig. 3

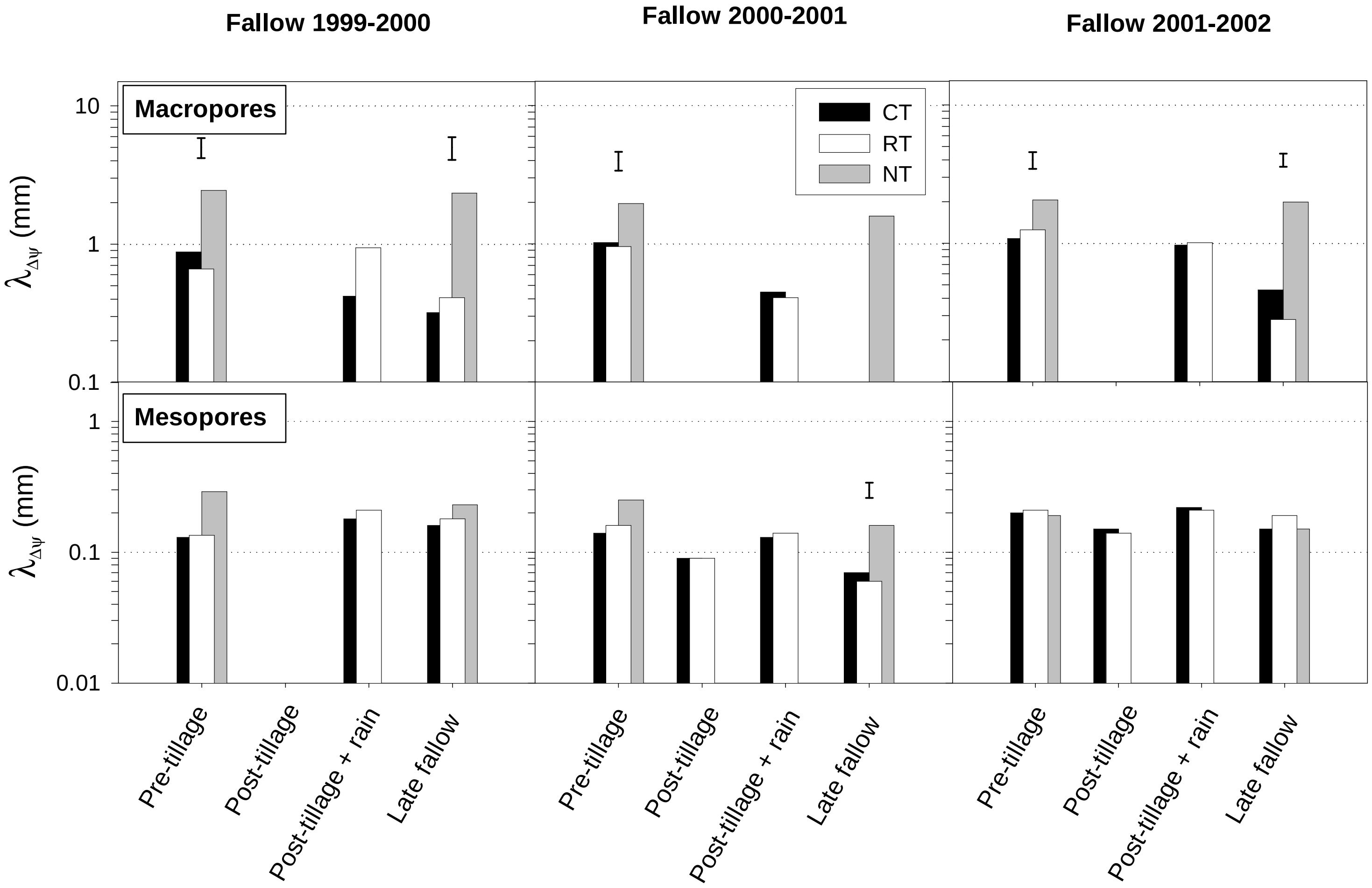
Fallow 1999-2000
Fallow 2000-2001
Fallow 2001-2002
Macropores
Mesopores
CT
RT
NT
$\lambda_{\Delta\psi}$ (mm)
10
1
0.1
0.01
Pre-tillage
Post-tillage
Post-tillage + rain
Late fallow

Fig. 4

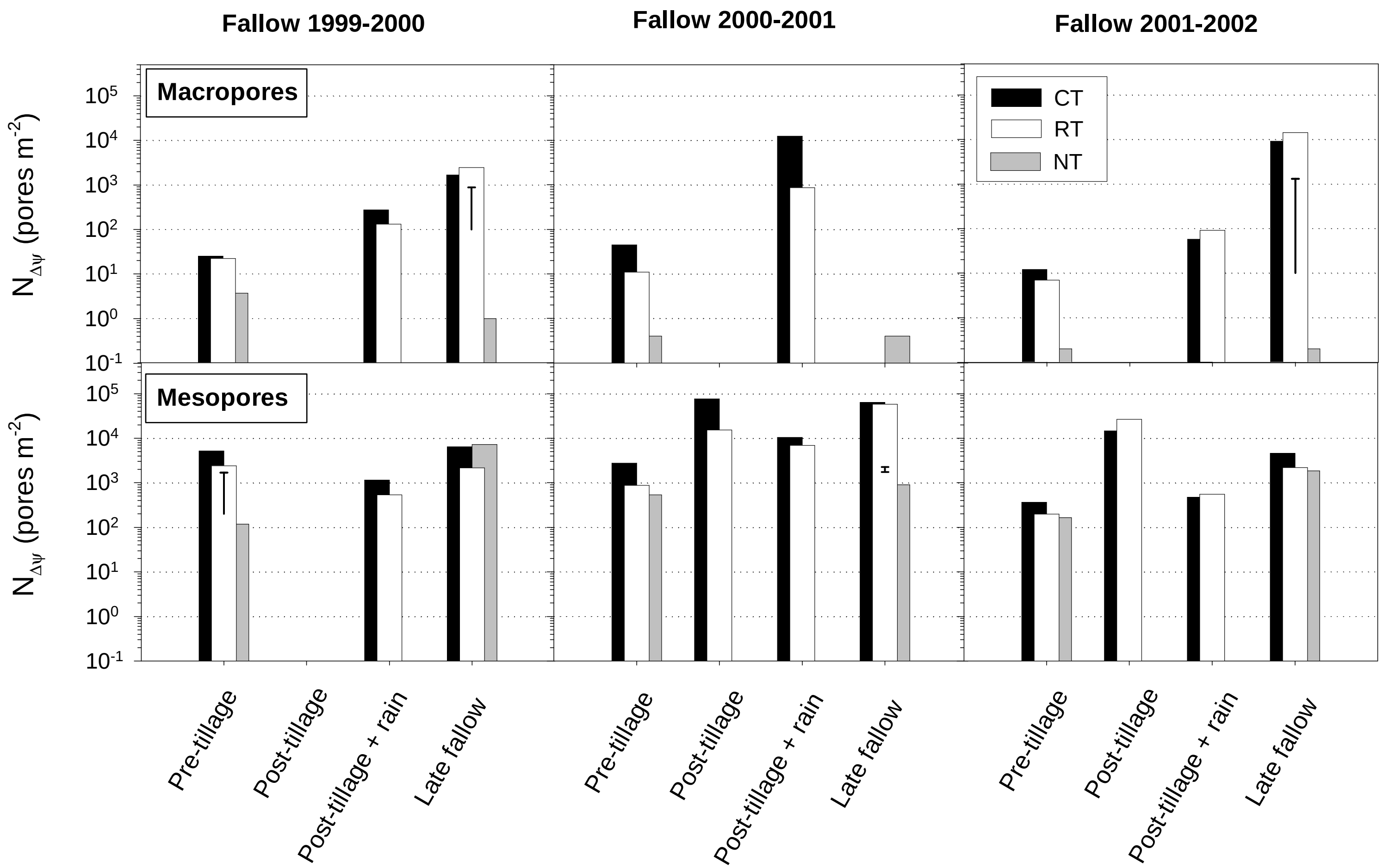
Fallow 1999-2000
Fallow 2000-2001
Fallow 2001-2002
Macropores
Mesopores
CT
RT
NT
$N_{\Delta\psi}$ (pores m^{-2})
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
Pre-tillage
Post-tillage
Post-tillage + rain
Late fallow

Fig. 5